AR-010-356

DSTO

Heat Acclimation Procedures: Preparation for Humid Heat Exposure

Nigel A.S. Taylor, Mark J. Patterson,
Jodie M. Regan and Denys Amos

DSTO-TR-0580

APPROVED FOR PUBLIC RELEASE

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Heat Acclimation Procedures: Preparation for Humid Heat Exposure

Nigel A.S. Taylor#, Mark J. Patterson#, Jodie M. Regan# and Denys Amos

DSTO-TR-0580

ABSTRACT

Thermal homeostasis is rigorously challenged under extremely hot conditions, particularly during prolonged exercise, with even highly trained individuals failing to maintain thermal homeostasis. As a consequence, the incidence of heat illness increases, particularly during the first five days of heat exposure. However, humans have evolved so that heat dissipation and conservation mechanisms are able to adapt to a range of environmental conditions. These physiological changes can be brought about in response to acute natural climatic changes, artificial heat exposure and to endurance exercise training. This report summarises the physiological changes accompanying heat adaptation and critically reviews heat adaptation procedures. Finally, recommendations are made concerning the implementation of heat adaptation procedures for military personnel. These recommendations include: specification of the thermal environment; the level of thermal strain; the use of exercise; exposure duration; and the subsequent maintenance of heat adaptation.

RELEASE LIMITATION

Approved for public release

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

University of Wollongong

Published by

DSTO Aeronautical and Maritime Research Laboratory
PO Box 4331
Melbourne Victoria 3001 Australia

Telephone: (03) 9626 7000
Fax: (03) 9626 7999

AR-010-356
October 1997

Heat Acclimation Procedures: Preparation for Humid Heat Exposure.

Executive Summary

During military operations and exercises in northern Australia soldiers frequently have been transferred from duties in the cooler southern states and have been required to function at peak military efficiency shortly after arrival in the hotter north. Such soldiers have not been thermally acclimatised and, anecdotally, are prone to varying degrees of heat strain during operations. Heat illness occurs most frequently during the first five days of heat exposure with heat exhaustion, an inability to continue work, the most common heat disorder. Humans have evolved so that heat dissipation and conservation mechanisms are able to adapt to a range of environmental conditions, as well as to the combined thermal stresses of exercise and external heat. These physiological changes can be brought about in response to acute natural climatic changes, to artificial heat exposure and to endurance exercise producing significant elevations in body core temperature.

This report summarises the physiological changes accompanying heat adaptation, critically reviews heat adaptation procedures and makes recommendations concerning the implementation of heat adaptation procedures for military personnel. It is proposed that heat acclimation which employs exercise in the heat, in combination with a controlled hyperthermia technique, provides the most reliable and safest means by which to acclimate ADF personnel to heat stress.

Several general principles for the heat acclimation process are described. Dry heat adaptation does not provide optimal protection for humid heat exposure and therefore it is advisable to use a hot-humid stress which permits both heat adaptation and psychological adjustment. The ambient temperature for acclimation should be equivalent to the highest anticipated maximum air temperature and, where possible, elevated by 5-10°C to magnify thermal stress. It is recommended that body core temperatures are elevated to at least 38.5°C to ensure an adequate sweat response. Any exercise mode which elevates core temperature is suitable; bench stepping is both cheap and well suited for multiple person acclimation. For extended field exposures, protocols should be based on single, daily exposures of approximately 100 minutes. Ideally the programs should last as long as possible, with 14 days being the minimum to ensure complete adaptation. Shorter programs may be used when time is limited; it is recommended that a minimum of 4 days be used with optimal benefits being gained from an 8 day protocol. It is imperative that subjects drink adequately between each phase of acclimation. The benefits of heat acclimation are transient and rapidly disappear if not maintained by repeated exposure to heat. It is recommended that one additional heat exposure be used for each 5 days away from significant heat exposures.

Authors

Nigel A.S. Taylor
University of Wollongong

Nigel Taylor is a Senior Lecturer in the Department of Biomedical Science, University of Wollongong specialising in Exercise and Environmental Physiology. He has collaborative research involvements with Aeronautical and Maritime Research Laboratory and the Naval Medical Research Institute (Bethesda, U.S.A.) which include human heat tolerance, cold-water adaptation and the provision of physiological specifications for breathing apparatus. Other research projects include investigations into human sweat regulation, heat adaptation, and the interaction of physical activity and ageing.

Mark J. Patterson
University of Wollongong

Mark Patterson is a doctoral candidate in Environmental Physiology, Department of Biomedical Science, University of Wollongong. Past and present research projects include investigating the influence of upper body skin temperatures on the control of sweat secretion, and the regulation of human body fluids during heat adaptation.

Jodie M. Regan
University of Wollongong

Jodie Regan is a doctoral candidate in Environmental Physiology, Department of Biomedical Science, University of Wollongong. Past and present research projects include human heat adaptation, and the effects of cold acclimation on human body-fluid distribution.

Denys Amos
Combatant Protection and Nutrition Branch, AMRL

Denys Amos graduated from the University of Durham (UK) in 1960 with a BSc(Hons) and MSc (1961) in organic chemistry. He has worked with ICI and the Science Research Council and has been attached to CBDE in the UK. At AMRL he has undertaken extensive research into the decontamination and into protection of

personnel against toxic chemicals. At present he is a Principal Research Scientist and manager of a program on personnel protection and physiological performance. Recently he has been the principal investigator into the physiological assessments of soldier performance in the tropics and the newly developed Chemical, Biological Combat Suit.

Contents

1. Introduction

1.1 Overview of physiological adaptations to repeated heat exposure.

Human thermal homeostasis is rigorously challenged under extremely hot conditions, particularly during prolonged exercise. The combination of prolonged exercise and heat exposure forces the cardiovascular system to provide blood flow to exercising skeletal muscles to satisfy metabolic demands, and blood flow to the skin to dissipate the heat released from the exercising muscles (Rowell, 1974). Most people can meet this dual demand, at least for a short duration. However, during prolonged exercise in the heat, even highly trained individuals may fail to maintain thermal homeostasis, and will move into positive heat storage. In such situations, the cardiac output is inadequate to fuel the combined demands for skin and muscle blood flow (Kenney and Johnson, 1992). When this occurs, blood pressure declines, as the volume of blood in the dilated capacitance vessels exceeds the circulating blood volume. The maintenance of blood pressure becomes the most important factor in the heat stressed individual (Rowell, 1974), and cutaneous vasoconstriction prevents pooling of blood in dependent cutaneous veins. Once this point is reached, heat dissipation is compromised, and continued exercise will rapidly elevate body core temperature (T_c), eventually leading to physiological dysfunction and heat illness.

Heat illness occurs most frequently during the first five days of heat exposure (Armstrong and Maresh, 1991), with heat exhaustion, an inability to continue work, the most common heat disorder. However, humans have evolved so that heat dissipation and conservation mechanisms are able to adapt to a range of environmental conditions, as well as to the combined thermal stresses of exercise and external heat. These physiological changes can be brought about in response to acute natural climatic changes (acclimatisation: Hellon *et al.*, 1956), artificial heat exposure (acclimation: Nadel *et al.*, 1974; Roberts *et al.*, 1977, Wells *et al.*, 1980), and to endurance exercise producing significant elevations in body core temperature (Gisolfi and Robinson, 1969; Henane *et al.*, 1977; Pandolf *et al.*, 1977).

The reduced physiological strain following both acclimatisation and acclimation is mediated by several adaptations (Table 1). There is an elevation of skin blood flow (SkBF) in response to heat stress and a lowering of the vasodilatory threshold (Fox *et al.*, 1963), facilitating the rapid transfer of central body heat to the periphery. The plasma volume expands, following a reduction in plasma protein loss to the interstitial fluid (Senay, 1979). This allows the stroke volume to increase and cardiac frequency (f_c) to be reduced (Mitchell *et al.*, 1976; Shapiro *et al.*, 1981; Cadarette *et al.*, 1984). These changes permit a reduction in both mean skin temperature (T_{sk}) and T_c for a fixed level of exercise and heat stress (Mitchell *et al.*, 1976; Pandolf *et al.*, 1977; Houmard *et al.*, 1990).

Table 1. Summary of physiological adaptations induced by combined exercise and heat stress.

Reference	T_c	T_{sk}	f_c	SkBF
Hellon and Lind (1955)	--	--	--	↑
Wood and Bass (1960)	--	--	--	⇔
Fox et al. (1963)	--	--	--	↑
Shvartz et al. (1973)	↓	↓	--	--
Nadel et al. (1974)	↓	--	↓	--
Mitchell et al. (1976)	↓	--	↓	--
Roberts et al. (1977)	↓	⇔	↓	↓
Pandolf et al. (1977)	↓	↓	--	--
Shvartz et al. (1979)	↓	↓	↓	--
Avellini et al. (1980)	↓	⇔	⇔	--
Shapiro et al. (1981)	↓	↓	↓	--
Avellini et al. (1982)	↓	↓	↓	--
Cadarette et al. (1984)	↓	--	↓	--
Havenith and van Middendorp (1986)	↓	↓	↓	↓
Pandolf et al. (1988)	↓	--	↓	--
Houmard et al. (1990)	↓	⇔	↓	--
Nielsen et al. (1933)	↓	--	↓	↑

Abbreviations: T_c = core temperature; T_{sk} = mean skin temperature; f_c = cardiac frequency; SkBF = skin blood flow; ↑ = variable increases; ↓ = variable decrease; ⇔ = variable unchanged; -- = variable not reported.

Finally, there is an enhancement of the sweat (sudomotor) response. Sweating is our most effective means of dissipating heat within hot environments, and improved evaporative cooling represents our most powerful adaptive response. Specifically, there is an increased sweat rate (m_{sw} : Libert *et al.*, 1983; Sato *et al.*, 1990), increased sweat gland sensitivity relative to T_c, and a decreased T_c threshold for sweating (Nadel *et al.*, 1974). The sweat glands also reabsorb a greater amount of sodium and chloride from the primary sweat, leading to a greater conservation of electrolytes (Allan and Wilson, 1971). While similar sudomotor responses may be induced with physical training in a neutral environment (Nadel *et al.*, 1974; Avellini *et al.*, 1982; Henane *et al.*, 1977), greater enhancement is typically induced through regular heavy exercise in the heat. These sudomotor adaptations to combined exercise and heat stress, summarised in Table 2, can result in a doubling of the peak hourly m_{sw} to 2-3 $l \cdot h^{-1}$, and minimise the effects of thermal stress upon the internal environment, permitting reduced strain and elevated heat tolerance, both at rest and during exercise.

Table 2. Summary of sudomotor adaptations induced by combined exercise and heat stress.

Reference	Total m_{sw}	m_{sw} threshold	m_{sw} sensitivity
Fox et al. (1963)	↑	--	--
Fox et al. (1964)	↑	--	--
Henane and Valatx (1972)	--	↓	--
Gisolfi (1973)	⇔	--	--
Henane and Valatx (1973)	--	--	⇔
Chen and Elizondo (1974)	↑	--	--
Nadel et al. (1974)	--	↓	↑
Mitchell et al. (1976)	↑	--	--
Henane et al. (1977)	--	↓	↑
Roberts et al. (1977)	--	↓	↑
Shvartz et al. (1979)	--	⇔	↑
Avellini et al. (1980)	↑	⇔	--
Candas et al. (1980)	↑	--	--
Wells et al. (1980)	--	↓	↑
Davies (1981)	--	↓	--
Avellini et al. (1982)	--	--	↑
Libert et al. (1983)	--	--	↑
Cadarette et al. (1984)	--	↓	--
Havenith and van Middendorp (1986)	↓	↓	↑
Pandolf et al. (1988)	--	⇔	⇔
Sato et al. (1990)	↑	--	--
Nielsen et al. (1993)	↑	--	↑

Abbreviations: m_{sw} = mean sweat rate; threshold = T_c at sweat onset; sensitivity = change in m_{sw} per unit rise in T_c; ↑ = variable increases; ↓ = variable decreases; ⇔ = variable unchanged; - - = variable not reported.

2. General Considerations.

2.1 Operational considerations for the selection of heat acclimation protocols.

Before one can choose and implement an appropriate heat acclimation procedure for either military or civilian purposes, a number of important preliminary considerations must be addressed. Section Three of this report presents an overview of six general means by which heat adaptation may be achieved. However, the selection of the most appropriate technique is dependent upon consideration of the points noted below.

2.1.1 Safety:

Whenever heat acclimation is attempted, there is some degree of danger to the subject. In military situations, for reasons of speed and efficiency, there exists a need to acclimate a number of people simultaneously. This practice magnifies the inherent risk associated with exercising in the heat. However, this risk can be minimised through the following procedures.

(a) **Monitor the T_c and f_c of each individual** during heat acclimation. This may be performed by medical/technical staff, trained observers, or by the subjects themselves.

(b) **Terminate exposure** when either index reaches a predetermined safety threshold. While such thresholds may vary between organisations, they should be consistent within an organisation, and should be based upon criteria known to reflect the probability of heat illness (*e.g.* Wyndham and Heyns, 1973).

(c) **Identify subjects most likely to experience dysthermia** prior to commencing heat acclimation. This involves the identification of states which could predispose an otherwise healthy person to heat illness (*e.g.* sleep deprivation, infectious disease, excess fatigue, various medications, recent alcohol or drug abuse), as well as the identification of people whose present physical status elevates the risk of heat disorder (*e.g.* obesity, poor level of fitness, cardiovascular disease). Strategies may then be developed for dealing with these people: *e.g.* elimination from environments or duties which create exposure risks; development of special heat acclimation regimens and safety precautions. The following general guidelines are noted for consideration (see: Wyndham, 1973):

* personnel with VO_{2peak} < 40 $ml \cdot kg^{-1} \cdot min^{-1}$ may be considered heat intolerant;
* personnel over 40 years will be at greater risk of heat disorder;
* personnel less than 50 kg will be at greater risk of heat disorder;

Table 3 Probability of heat disorders (T_{re} >40°C) in acclimated and unacclimated personnel of varying cardiorespiratory fitness levels (Wyndham, 1973).

	VO_{2peak}	Probability	n
Unacclimated	< 2 L.min-1	0.17	9
	2 - 2.5 L.min-1	0.045	19
	2.5 - 3 L.min-1	0.018	7
	>3 L.min-1	0.009	6
Acclimated	< 2 L.min-1	no estimate	4
	2 - 2.5 L.min-1	0.03	13
	2.5 - 3 L.min-1	0.0003	12
	>3 L.min-1	<0.0001	12

Abbreviations: VO_{2peak} = peak aerobic power; *n* = number of subjects used to determine probability estimates.

(d) **Establish emergency procedures** capable of handling all likely medical complications. All commanders, medical personnel and observers should be familiarised with the standard signs and symptoms of heat disorders, and be trained in standard emergency procedures.

2.1.2 Efficiency.

The best form of acclimation may well be natural acclimatisation. However, from the perspective of military groups, this may be neither possible nor practical. Therefore, one must consider how to most efficiently acclimate such people. The following points should be considered.

(a) **Efficiency of personnel.** What combat to support personnel ratio is deemed acceptable on both safety and economic grounds? What is the availability of support staff?
(b) **Throughput.** How many people need to be acclimated simultaneously?
(c) **Acclimation duration.** What is the maximal time (number of days, hours per day) available to devote to heat acclimation?
(d) **Acclimation decay.** Since military groups may use acclimation procedures prior to transporting soldiers to hot regions, it is important to know the delay time between the

soldiers' final acclimation exposure and arrival at their destination. This will permit careful prescription of post-acclimation and pre-arrival activities to minimise acclimation decay.
(e) **Individual needs.** Do all personnel have the same requirement for heat acclimation? Are some individuals already heat acclimated? Are there some activities in which heat acclimation is a high or low priority?
(f) **Availability of the acclimation facility.** Can military personnel come to a fixed acclimation centre(s), or do operational requirements dictate that a mobile acclimation station be able to travel to the theatre of operations?

2.1.3 Acclimation specifications:

A prescription for heat acclimation is dependent upon a detailed analysis of the operational heat acclimation requirements. This provides specifications within which the safest, most efficient and most appropriate procedures can be established. The following points provide input to such specifications.

(a) **The basal acclimation state of soldiers.** In the military environment, data should be obtained which classifies personnel according to acclimation status and physical fitness. It may be possible to broadly classify the acclimation status of personnel according to the predominant regional climatic conditions and then to sub-classify personnel within these regions according to physical fitness. As an operational definition, it is suggested that basal acclimation could be identified using a standard heat stress test (*e.g.* Turk, 1974) to which a terminal T_c threshold of 38^{o}C could be used to identify those who require test acclimation treatment (after: Dreosti, 1935). It may also be possible to establish an index of acclimation state based upon the m_{sw} : T_c relationship, as recommended by Havenith and van Middendorp (1986).

(b) **Worst case thermal stress.** What is the most stressful set of conditions to which personnel will be exposed? Consideration here must be given to: environmental conditions (ambient temperature and humidity); anticipated work loads (daily average and peak work rates); clothing ensembles (normal and protective clothing).

(c) **The level of heat acclimation required.** From a consideration of the points above, what levels of heat acclimation will be deemed minimal and optimal? Will a partial acclimation be acceptable? For example, in a situation where time is critical, it may be possible to shorten acclimation, allowing the final stages of adaptation to occur within the field, but under restricted duties or conditions.

(d) **Definition of heat acclimation.** Since heat acclimation is a continuum, with distinctly different short- and long-term phases (Horowitz and Meiri, 1993; Libert *et al.*, 1988), and since different physiological variables plateau at different points during acclimation (Armstrong and Maresh, 1991), it is essential to establish criteria for determining acceptable levels of acclimation (*e.g.* attainment of plateau). Which physiological variable will be monitored as an index of acclimation state (*e.g.* T_c, f_c, m_{sw})? All three of these variables are indices of thermal strain, and impart

information about the progress of acclimation. However, f_c is more closely related to cardiovascular fitness, while T_c and m_{sw} are better correlated with acclimation state (Havenith and van Middendorp, 1986).

(e) **Critical heat exposure work duration.** It is well known that heat acclimation protocols lasting one to two hours provide minimal protection when workers are faced with heat stress duties lasting four hours or longer (Avellini *et al.*, 1980; Wyndham, 1973). Accordingly, detailed operational duties and schedules become fundamental background information for the development of heat acclimation regimens.

(f) **Test of heat acclimation.** Turk (1974) has recommended the following simple test to assess heat acclimation status : one hour bench stepping (30.5 cm step), 12 steps per minute, 47.7°C (31.7°C wet bulb). Failure to maintain T_c <38°C (after: Dreosti, 1935) constitutes test failure.

3. Heat Acclimation Procedures.

3.1 General overview of the principles and practices of heat acclimation.

While it is generally recognised that natural acclimatisation is the best means by which to acquire heat tolerance (Edholm *et al.*, 1963), it is usually not possible for all people to utilise such an adaptation procedure. For example, military personnel require the ability to rapidly move from one environment to another without suffering either the consequences of dysthermia, or reduced work rates during the adaptation period. Since thermal adaptation may result from stresses other than those of direct thermal origin, organisations have employed a variety of heat adaptation techniques to induce positive cross adaptation. These methods facilitate various levels of pre-exposure heat adaptation, and may be considered to fall into six general acclimation categories. The following sections contain general overviews of these techniques and brief methodological critiques.

3.1.1 Passive heat acclimation.

Since both endogenous and exogenous heat sources give rise to acclimation responses (Hensel, 1981; Wells et al., 1980), heat adaptation can be induced by passively raising the T_c through the application of heat at the skin surface. This has been achieved using water baths, saunas, climate chambers and vapour-barrier suits (Fox et al., 1963, 1964, 1967; Fox, 1968; Sugenoya et al., 1986; Ogawa et al., 1988; Inoue et al., 1995). The most sophisticated of these techniques was developed using the last technique, in which vapour-barrier suits were used to clamp an elevated T_c (Fox et al., 1963, 1964, 1967; Fox, 1968). This method is generally described as *`controlled passive hyperthermia'*, with its critical feature being the regulation of an elevated T_c. Since this group was aware

that it was the stress provided by an elevated deep body thermal input that was the essential stimulus to acclimation, they developed the following method:

(a) Rapid T_c elevation to 38°C with exercise in the heat (40°C);
(b) Dress subjects in vapour-barrier suits; and
(c) Clamp T_c by placing subjects in a room at 38°C for 2 h, and venting the suit to regulate heat loss.

While this method proved most successful at achieving an acclimation effect (Fox et al., 1963, 1964, 1967; Fox, 1968), passive acclimation generally is believed to be less effective than methods which incorporate an exercise stress into the acclimation regimen (Shapiro et al., 1981; Wyndham, 1973), making it both a protracted and an unpleasant procedure to produce a sufficiently high elevation in core temperature.

3.1.2 Exercise-induced heat adaptation:

It has long been known that exercise elevates T_c, and that this elevation is directly related to the intensity of the exercise stress (Nielsen, 1938; Saltin & Hermansen, 1966). Since habitual exercise of sufficient intensity and duration not only elevates T_c, but acts to maintain this elevation over an extended period, then exercise can induce heat adaptation responses. This was first suggested by Robinson et al., (1943), Bean and Eichna (1943), and Bass et al. (1958). In fact, Greenleaf (1964) and Piwonka et al. (1965) have described their trained subjects as behaving in the heat as if they were already acclimatised. Such increased heat tolerance with training has been attributed to stimulation of both the sweat glands and skin blood flow (Piwonka et al., 1965). For example, increased evaporative heat loss is facilitated by an earlier sweat onset (Nadel, 1979) and a greater sweat sensitivity (Wells et al., 1980). Moreover, an elevation in aerobic power (VO_{2peak}) accompanying training permits a greater cardiovascular stability (Gisolfi and Robinson, 1969; Wells et al., 1980), and more favourable body-fluid dynamics (Senay, 1979). In fact, it has been suggested that the essential component of exercise in any heat acclimation programme is due to its effects upon the cardiovascular system, and the manner in which those adaptations facilitate heat dissipation (Wyndham, 1973).

A further advantage of training is that subjects who possess an elevated basal fitness level appear to respond more rapidly to traditional heat acclimation protocols (combined exercise and heat stress) than do more sedentary subjects ($r = -0.68$: Pandolf *et al.*, 1977; Cohen and Gisolfi, 1982). Pandolf *et al.* (1977) found that subjects with a VO_{2peak} greater than 65 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ could be acclimated to achieve a stable heat stress f_c and T_c within about four days[1]. Furthermore, subjects who show a retarded acclimation response often do so because they have a low basal fitness level (Kok,

---

[1] It is important to exercise caution here. While numerous forms of exercise elevate VO_{2peak}, only those forms of exercise which also elevate T_c may be considered applicable to this relationship. Thus, it is not necessarily a high VO_{2peak} *per se* that enhances the heat acclimation response, but the manner in which the VO_{2peak} was elevated (*i.e.* the mode of training).

1973). Consequently, the early part of the traditional acclimation regimen acts more to elevate fitness than it does heat adaptation, and such subjects require longer acclimation periods to achieve a satisfactory acclimation status.

Various groups have studied the efficacy of *exercise-induced heat adaptation*, producing data ranging from full support of the technique (Gisolfi and Cohen, 1979) to that which shows little advantage at all (Turk and Worsley, 1974). However, it is clear from studies conducted on swimmers (Hennane *et al.*, 1977), and the sweatless training work of Hessemer *et al.* (1986), that exercise *per se* is not a sufficient stimulus to induce heat adaptation. The exercise regimen must induce, and hold, an elevated T_c to provoke adaptations conducive to greater heat tolerance.

Numerous exercise regimens have been tested over the past 50 years. However, the major limitation of the vast majority of the research conducted on this theme is the disregard for the need to monitor and report changes in T_c. Many such studies have revealed equivocal evidence. Most of these results could simply be explained on the basis of a failure of the exercise regimen to adequately elevate T_c. For example, Edholm *et al.* (1963) and Turk and Worsley (1974) relied upon traditional military training, regulated by drill instructors, to provide an assessment of the efficacy of exercise-induced heat adaptation. Similarly, groups such as Cohen and Gisolfi (1982) have evaluated the effects of different training intensities upon subsequent heat tolerance, but without monitoring the impact of these protocols upon T_c. While such work is often cited within the literature, it is not possible to draw scientifically sound conclusions from these studies. Exceptions to this include the work of Shvartz *et al.* (1973) and Regan *et al.* (1996), both of which have shown that exercise-induced heat adaptation is not as effective as traditional heat acclimation. On the basis of first principles knowledge, and a distillation from the literature, the following general points appear valid.

(a) Exercise-induced heat adaptation depends upon the capacity of the exercise regimen to sufficiently elevate T_c, and to hold that elevation for a sufficiently long period.

(b) This T_c rise is best achieved in conditions in which convective, conductive and radiative heat losses are minimised.

(c) Higher intensity exercise provides for a more rapid and greater elevation in T_c.

(d) Given that a minimal exercise intensity must be used to sufficiently elevate T_c, the total volume of training appears to be more critical than the intensity, once this minimal intensity threshold has been obtained (Pandolf et al., 1988).

(e) Continuous exercise will more reliably hold the elevated T_c than will intermittent exercise. This is best achieved using activities such as running, rather than callisthenics or routine military duties.

(f) The greatest improvements in heat tolerance appear to accrue to more protracted training programmes (Gisolfi, 1973; Henane et al., 1977).

In conclusion, the following points require noting. While physical training can induce a thermal adaptation, training only appears to provide this thermoregulatory benefit during heat exposures of about two hours or less (Wyndham, 1973). In addition, physical training, on its own, appears to be an inadequate substitute for combined exercise and heat acclimation (Armstrong and Pandolf, 1988; Gisolfi, 1973; Lind and Bass, 1963; Pandolf, 1979; Regan *et al.*, 1996). From this research, it is apparent that simply elevating T_c is not sufficient to induce complete heat adaptation, and that the elevation of peripheral tissue temperatures may provide a critical thermal stimulus to acclimation. *Once a sufficient basal fitness level has been attained, there appears to be no further thermoregulatory advantage to be gained from additional physical training* (Bean and Eichna, 1943; Eichna *et al.*, 1945). Finally, it should be noted that physical training and exercise-induced heat adaptation serve different purposes, and may require different exercise programmes. While strenuous exercise may improve heat tolerance, heat adaptation training may have only marginal impact upon the physical fitness of some trained people, particularly the well-trained athlete.

3.1.3 Exercise-induced heat adaptation with solar load.

There is a paucity of information concerning the differences in exercise-induced heat adaptation with and without a solar load. Direct solar radiation causes a much greater rise in mean T_{sk} than does heat produced within a laboratory, therefore evoking different physiological responses. Data collected from goats shows a totally different thermal response at a given air temperature when solar radiation is higher (Jessen, 1990). The critical point is that physiological systems adapt primarily to counteract stresses which disturb homeostasis. That is, there is a degree of specificity of adaptation. While there is ample evidence for a wide variety of positive cross adaptations (Hensel, 1981), such transfer is often more fortuitous than deliberate. Thus, while there is some heat adaptation transfer from training in temperate conditions to heat tolerance, one would not expect this transfer to equate with the adaptations induced by training in hot conditions, with a high solar load.

A few studies have addressed this issue, although perhaps more by chance than by design. Edholm *et al.* (1963), Wells *et al.* (1980) and Armstrong *et al.* (1987) each studied subjects who were exposed to direct solar radiation during a physical training programme. Edholm *et al.* (1963) compared the thermal tolerance of soldiers living in the Aden (6 weeks) with those living in Scotland. They found that natural acclimatisation resulted in the best heat adaptation. From subjective evaluations of military performance by officers, the naturally acclimated soldiers were superior. They also had fewer field-related casualties.

Wells *et al.* (1980) found that trained and acclimatised males, who regularly exercised under desert conditions, showed a better thermal adaptation than did either

unacclimatised or acclimatised groups. This suggested that both endogenous and exogenous heat loads were required for optimal heat adaptation.

Armstrong *et al.* (1987) studied the thermal responses, during spring and summer, in highly-trained distance runners who continued their regular training routines (northern U.S.A.) with their own coaches. Since these people were both highly trained endurance athletes and continued their training outside, they would be exposed to both a high endogenous and exogenous thermal loads, particularly during the summer months. However, the results showed no significant difference between heat tolerance before and after summer training. This does not mean that athletes were optimally heat adapted, just that their adaptation state did not improve further over summer. While these data do not indicate that solar loading is necessary for optimal exercise-induced heat adaptation, they are consistent with those of Bean and Eichna (1943) and Eichna *et al.* (1945): no further thermoregulatory advantage is gained from additional physical training once a minimal basal fitness has been attained. The practical implication from this work is that highly-trained endurance runners may not need special preparation for summer competition[2].

Given the relative shortage of research that has directly addressed the question of solar loading, it is difficult to draw firm conclusions concerning this approach. Nevertheless, since this type of exposure most closely approximates the conditions that would exist with natural acclimatisation, it seems reasonable that this method would be superior to simply exercising within temperate conditions. However, the general comments and limitations concerning exercise-induced heat adaptation are again applicable.

3.1.4 Exercise-induced heat adaptation in combination with sweat clothing:

Interest in this type of heat adaptation stems from the work of Bass (1963) and Gisolfi and Robinson (1969). Since heat adaptation is elicited by raising T_c and T_{sk}, then it seems feasible that the wearing of sweat-proof clothing (*e.g.* vapour-barrier garments) during exercise could be used to facilitate heat adaptation. This would have great practical advantages over traditional heat acclimation protocols, since it would enable more people to be acclimated in a shorter time, and at a reduced expense. However, there is very little empirical evidence demonstrating that this procedure is any more effective than conventional physical training at inducing heat adaptation (Allan *et al.*, 1965; Crowdy *et al.*, 1965; Marcus, 1972; Dawson, 1994). [A more complete review of this material is contained within Dawson (1994)].

At present, on the basis of the available evidence, which is itself not of high scientific quality, there appears to be little physiological benefit to be gained from using sweat clothing during physical training. In fact, it would appear that, unless T_c is adequately

---

2 This does not translate to out-of-season competition, where athletes may be required to travel from their winter to compete in summer in the other hemisphere, or in rarely encountered climatic states. Under these circumstances, additional heat exposure may be required.

elevated and carefully regulated, this technique *offers no advantage over exercise-induced heat adaptation.*

3.1.5 Exercise-induced heat adaptation with controlled hyperthermia.

Only two research groups have used controlled hyperthermia within an exercise protocol, to elicit heat adaptation (Havenith and van Middendorp, 1986; Regan *et al.*, 1996). Most previous researchers, investigating exercise-induced heat adaptation, have neglected to control the thermal strain imposed upon their subjects. Instead, most have evaluated the efficacy of various regimens by simply comparing heat adaptation responses accruing to conditions ranging from unmonitored exercise through to extreme states of exercise and heat stress. Such methodological differences have meant that unequivocal data interpretation is almost impossible, and has made the identification of mechanisms driving heat adaptation difficult to differentiate. Moreover, since it is known that both T_c and mean T_{sk} changes elicit thermoregulatory responses, one might predict that such afferent signals play a powerful role in thermal adaptation. Indeed, Fox (1968) suggested an increase in T_c was the primary impetus for thermoregulatory adaptation. While Chen and Elizondo (1974), investigating differences between whole-body and local skin temperature effects on acclimation, concluded that an increased central stimulus (T_c), in conjunction with increased local skin temperature, was essential for heat acclimation. It is therefore more appropriate to compare and equate physiological strain between experimental conditions on the basis of thermal load imposed by those conditions, rather than on the basis of its secondary impact upon physiological function.

To compare exercise-induced heat adaptation with combined exercise and heat acclimation, Regan *et al.* (1996) equated between-condition thermal strain on the basis of T_c changes. Two groups of seven matched males, participated (1 hr per day, 10 days) in one of two conditions: (i) neutral physical training (22.4°C, relative humidity 41.0%); or (ii) combined physical training and heat acclimation (38.27°C, rh 39.7%). Controlled hyperthermia was induced by rapidly elevating rectal temperature by 1°C (cycling), then holding it constant by manipulating external work. Subjects completed three-phase heat stress tests (39.8°C, rh 38.6%), before and after acclimation. While there was a difference of 4.2°C in mean skin temperature between treatments, both regimes elicited a similar peripheral sudomotor increase indicating a core temperature-dependent adaptation. However, based on significant pre- versus post-acclimation decreases in T_c (0.4±0.1°C), forehead skin blood flow (26%), perceived exertion (11%), and a 5% increase in forehead m_{sw} (0.1±0.04 ml.cm^{-2}min^{-1}), the combined heat and exercise regimen was deemed to have elicited a more complete heat acclimation.

While elevation in T_c is critical to heat acclimation, it also appears necessary to expose subjects to an exogenous thermal stress. This observation has not been demonstrated previously under conditions of controlled hyperthermia, and verifies the importance of skin temperature elevation in the heat acclimation process. Furthermore, and in accordance with the observations of previous groups (Armstrong and Pandolf,

1988; Gisolfi, 1973; Lind and Bass, 1963; Pandolf, 1979), this work demonstrates that exercise-induced heat adaptation is not as effective as combined heat and exercise acclimation, even when both conditions elicit an identical deep body thermal strain.

3.1.6 Combined exercise and heat stress acclimation.

Traditionally, heat acclimation protocols have involved the use of moderate-to-heavy exercise (walking, running, cycling, bench stepping) within a temperature-controlled laboratory. Such protocols are universally recognised as being superior to exercise-induced heat adaptation procedures (Wyndham, 1973), and may be broadly categorised into one of three general forms:

(a) Constant work rate protocols: These protocols represent the most commonly used acclimation methods. There are almost a limitless array of ambient conditions and exercise regimens that have been employed to induce heat acclimation (see reviews by Greenleaf and Greenleaf, 1970 and Sciaraffa *et al.*, 1980), however, the critical factor is the simple and protracted elevation of T_c within a hot environment. Subjects exercise at a fixed rate, with T_c simply tracking heat storage, as heat production exceeds heat dissipation. Since all subjects will be exercising at the same absolute intensity, T_c and f_c will vary widely between subjects, and these variables are monitored to ensure subject safety.

(b) Self-regulated exercise protocols: Within a set environmental state, subjects are given a prescribed work : rest regime within which they select their own work rates, according to their fitness and personal sense of effort during the course of acclimation. Again, T_c will vary between subjects, but to a smaller extent, since subjects are regulating their own work rate, T_c and f_c are monitored for safety reasons. (Miller, 1984; Armstrong *et al.*, 1986).

(c) Controlled hyperthermia protocols: Under these procedures, subjects exercise in the heat, monitoring their own T_c, and adjusting their work rate to elicit a predetermined and constant level of mild hyperthermia. (Turk, 1974; Turk and Worsley, 1974). We recommend the use of this paradigm to elicit heat acclimation.

4. Recommended Heat Acclimation Procedures.

As previously noted, physical training and combined exercise-heat acclimation serve different purposes, and may require different exercise programmes. While strenuous exercise may improve heat tolerance, heat acclimation will have only marginal impact upon physical fitness in the trained person, particularly when using the controlled hyperthermia procedure. This point is particularly significant to athletic groups, since they must remember that regular training must continue, *albeit* in conditions more conducive to greater stress tolerance, with acclimation training merely acting to enhance heat tolerance and not to replace normal training programmes. In such groups, heat acclimation is a form of supplementary exercise.

Because the magnitude of the acclimation effect is proportional to the size of the thermal load imposed upon the subject, it is our view that *heat acclimation which employs exercise in the heat, in combination with the controlled hyperthermia technique, provides the most reliable and safest means by which to acclimate* people to heat stress. This technique allows for prescription of the size of the thermal load (T_c elevation), which can then be closely monitored. While any heat acclimation procedure is inherently hazardous, this technique produces more uniform elevations in T_c, which are continuously monitored by both the subjects and trained observers. Nonetheless, like other physiological adaptations, heat acclimation is specific to the regimen utilised, and heat tolerance may not be readily transferred to stresses of different durations, exercise intensities or environmental conditions. To adequately implement this procedure several critical questions must be considered.

4.1 Does acclimation to dry heat provide adequate acclimation for humid heat?

Heat acclimation to dry and humid heat produces slightly different physiological responses. Humid heat acclimation results in a greater elevation in mean m_{sw} than does dry heat acclimation (Henane, 1980; Shvartz *et al.*, 1973). However, Shvartz *et al.*, (1973) found that when subjects were exposed to hot-dry conditions (50°C), following either hot-humid or hot-dry heat acclimation, the hot-dry exposures produced a greater reduction in thermal strain (see also: Eichna *et al.*, 1950; Gisolfi and Robinson, 1969; Piwonka and Robinson, 1967). From the perspective of simply providing a generalised state of heat acclimation, it appears that hot-dry exposures should be employed. However, dry adaptation does not provide optimal protection for humid exposures (Armstrong *et al.*, 1987). Consequently, if one knows that personnel are about to enter a hot-humid environment, then *it would be better advised to use a hot-humid stress, since it permits both heat adaptation* (Fox, 1968; Garden *et al.*, 1966; Shvartz *et al.*, 1973), *and psychological adjustment* to anticipated environmental conditions.

4.2 What ambient temperature should be utilised?

Having decided upon the use of dry- or humid-heat exposures, one must decide upon the dry bulb temperature (T_{db}) to be used. It is impossible to provide a rigid prescription for this temperature. However, the following guidelines are offered:

(a) Select a T_{db} which is at least equivalent to the highest anticipated air temperature in the environment for which subjects are being acclimated.
(b) Where possible, elevate this temperature a further 5-10°C to magnify the thermal stress imposed. The key component of the current recommendations is the use of controlled hyperthermia to induce acclimation, therefore the precision of the T_{db} selection is less critical.
(c) The upper T_{db} limit should be about 40°C for humid exposures (*i.e.* >60% relative humidity) and about 50°C for dry exposures (*i.e.* <30% relative humidity).

4.3 What level of thermal strain (T_c) should be achieved during acclimation?

The controlled hyperthermia technique was developed using T_c elevations of 38.0 - 38.8°C (Fox *et al.*, 1963; Turk and Worsley, 1974), while others have used fixed elevations above pre-exposure T_c (Regan *et al.*, 1996). While it is not possible to prescribe an exact T_c target necessary for effective heat acclimation within all circumstances, the following points can be used to derive such a prescription:

(a) In general, the greater the T_c elevation, the greater will be the heat adaptation. However, the greater the change in T_c the more stressful is the acclimation regimen. Thus, it is important to consider the relative importance of the acclimation protocol within the general duties of the subjects. For example, in military personnel it may be that time can be devoted solely to heat acclimation, whereas athletes must be sufficiently recovered from their acclimation training to continue their normal training programme.

(b) The magnitude of the T_c elevation dictates the level of risk accompanying heat acclimation. Clearly, with closely supervised, one-on-one heat acclimation, higher T_c increments may be achieved with less threat to subject safety. We strongly advise against exceeding 39.5°C under any circumstance.

(c) There is some evidence to indicate that mean m_{sw} during acclimation should exceed 400-800 $mL{\cdot}h^{-1}$ for adequate sudomotor adaptation (Armstrong *et al.*, 1985; Sciaraffa *et al.*, 1980). While subjects vary considerably in the sweat response to heat, it is our experience that a 1°C in T_c, held for about 60 min in 36°C, will result in a mean m_{sw} of about 0.9-1.0 $L{\cdot}hr^{-1}$. It is therefore recommended that a minimal T_c elevation of 1°C be implemented. For simplicity, it is best to translate this into a given T_c, so that both subjects and observers can readily and simply note the progress of each subject.

(d) Since we recommend subject-monitored controlled hyperthermia, consideration should be given to both the desired T_c target, and the T_c target given to each subject. Because subjects vary in their ability to hold T_c targets (Turk and Worsley, 1974), it is probably worth asking subjects to hold targets 0.3-0.5°C greater than the desired target, thus ensuring that all subjects will meet at least a common minimal elevation.

(e) The duration of the exposure, and the number of exposures to be used should be considered when determining the magnitude of the T_c elevation, since these all determine physiological strain. In general, if time is critical, a greater T_c held for longer may be more desirable.

(f) The maintenance of high mean m_{sw} in humid heat is quite unpleasant for most subjects (Fox *et al.*, 1967). Accordingly, it is recommended that consideration be given to subject comfort as the acclimation progresses.

In consideration of these points, *we recommend that all subjects have their T_c elevated to 38.5°C.* This represents a hyperthermic load which will ensure an adequate sudomotor response, while being both safe and manageable for multiple-person treatments.

4.4 What exercise intensity should be employed during heat acclimation?

The mode of exercise used to induce heat acclimation is only critical within the athletic domain where the use of mode-specific ergometry has direct implications for performance outcomes. For military requirements, it is less critical, and any exercise mode which elevates T_c is suitable. The prime consideration is usually cost, and simple bench stepping is both cheap and well suited for use in multiple person acclimation programmes. Consideration should be given to subject boredom wherever possible, and it is suggested that the use of several forms of ergometry, utilised on a rotational basis, be implemented to maximise subject interest.

Given that we recommend the use of subject-regulated controlled hyperthermia, then the intensity of the exercise has little bearing on the efficacy of the protocol, except during the initial elevation of T_c. Here we recommend the procedures of Turk and Worsley (1974): bench stepping (30.5 cm step), at 18 steps per minute. After reaching the target T_c, subjects will implement their own work : rest routine, but when stepping, will continue to work at about 12 steps per minute.

4.5 How long should each exposure last?

Duration is very much dependent upon the decisions made above, since the combination of ambient temperature and exercise intensity determine the time it takes for T_c to elevate. However, the controlled hyperthermia technique permits one to concentrate more upon exposure duration, with less concern with exercise intensity, since the subjects will modify their work intensity to hold a constant T_c.

Wyndham (1973) has suggested that to acclimate for a full eight-hour shift (mining), acclimation exposures must be of at least four hours duration. Avellini *et al.* (1980) similarly found that a two-hour acclimation (repeated over six days) was inadequate when subjects were exposed to a four-hour heat stress test. It is tempting to suggest that these data indicate that acclimation exposures times should be at least 50% of the anticipated work time. While such an interpretation has not been empirically justified, for the purpose of this report, it does form a suitable basis for the general prescription of exposure times. In the light of these observations, the following recommendations are possible:

(a) When relatively *short exposures* are anticipated in the field situation (*e.g.* <~2 hours), with each exposure separated by an adequate recovery time (*e.g.* >1 hour), then it is recommended that *acclimation exposures be of at least equal duration* to those anticipated.

(b) When *longer exposures* are anticipated in the field situation (*e.g.* >3 hours), and when each exposure is separated by an adequate recovery time (*e.g.* >1.5 hour), then it is recommended that *acclimation exposures be of at least 50% of the anticipated duration, with the minimum duration being two hours.*

(c) When *extended field exposures* are anticipated (*e.g.* >4 hours), and when each exposure is separated by only a minimal (*e.g.* >1 hour) or uncertain recovery time, then it is recommended that:

(i) acclimation exposures be of at least 50% of the anticipated duration, with the minimum duration being three hours;

(ii) when recovery is very short, it should be considered to be absent, and all consecutive exposure durations should be summed to determine the duration of the acclimation exposure (as in (i)); and

(iii) where possible, given the circumstance noted in (ii), commanders should be encouraged to lengthen the rest periods between consecutive work exposures, to maximise soldier recovery.

Can this time be best achieved using single or multiple daily exposures? From the work of Lind and Bass (1963), it seems that the duration of the individual exposure is more important than the combined duration of two exposures repeated within a single day. That is, they found that a single 100 minute exposure proved better than two 50 minute exposures (morning and afternoon), which was only marginally better than a single 50 minute exposure. Accordingly, within this study, the most economical procedure was a single acclimation bout of 100 minutes. Since any given exposure is associated with a time delay, due to the time taken for tissue temperatures to rise to a critical temperature, then one long exposure would give more time at or above this critical temperature, than would two shorter exposures with same total time in the heat. Accordingly, it is *recommended that heat acclimation protocols be based on single, daily exposures of longer duration.*

4.6 How long should the acclimation programme be continued?

There are three distinct phases of heat acclimation: acute exposure which elevates T_c; short-term acclimation which produces an heightened mean m_{sw} response resulting in a sweat `overshoot' and sweat drippage; and long-term acclimation, in which there is a reduction in both mean m_{sw} and sweat drippage (Candas, 1987). Acclimation regimens must force subjects beyond the acute phase. Barnett and Maughan (1993) found no evidence of acclimation with repeated heat exposures spaced one week apart, while Libert *et al.*, (1988) found that subjects entered the third phase following three days (72

hours) of continuous heat exposure, during which exercise was a part of their daily routine.

Not all physiological variables respond at the same rate to heat acclimation. Thus, the determination of the attainment of the desired heat acclimation may vary according to the physiological variable chosen as the marker. From an overview of the constant work rate literature, Armstrong and Maresh (1991) have determined the approximate number of days required for adaptation to achieve about 95% of its maximal response. While this information is very much dependent upon the magnitude of the thermal stress, the humidity of the environment, the duration of the exposure and the magnitude of thermal strain achieved within experimental subjects, it does provide valuable information when considering the number of repeat exposures to adopt for an heat acclimation protocol.

(a) f_c decrease: 3-6 days;
(b) PV expansion: 3-6 days;
(c) reduced T_c: 5-8 days;
(d) reduced effort perception: 3-6 days;
(e) reduced sweat sodium and chloride excretion: 5-10 days;
(f) increased mean m_{sw}: 8-14 days; and
(g) reduced urine sodium and chloride excretion: 3-8 days.

Therefore, it takes up to fourteen days for all physiological systems to adapt completely.

Ideally, acclimation programmes should last as long as possible, with approximately 14 days being the minimal limit to ensure almost complete adaptation. Shorter duration programmes may be used when time is restricted. Under these circumstances, the efficacy of the programme will be a simple function of two factors: treatment duration (*i.e.* time of each exposure); and the duration of the anticipated heat exposure. Turk and Worsley (1974) have shown that 86% of their subjects could be acclimated within four days, using a one-hour controlled hyperthermia procedure. This was tested against a one-hour heat stress test. On the other hand, Wyndham (1973) found that to acclimate subjects for a full eight-hour shift (mining), acclimation must be at least four hours per day for ~8-9 days. We *recommend that a minimum of four days be used, with optimal benefits being gained from an eight day protocol*[3].

4.7 Should water be consumed during acclimation?

For safety reasons, it is imperative that subjects drink adequately, both prior to each acclimation treatment and during each phase of heat acclimation. Furthermore, there is evidence to show that acclimation may be impeded without adequate fluid

3 While 14 days provides maximal heat acclimation of most physiological systems, the additional six days produce slow and minimal daily improvements. From the perspective of time and efficiency, these additional days may not be warranted.

replacement (Pitts *et al.*, 1944). However it may be better to drink to replace lost mass after each exposure, rather than during each exposure.

4.8 Once acquired, how is heat acclimation best maintained?

The benefits of heat acclimation are transient, as opposed to those of physical training, and rapidly disappear if they are not maintained by repeated exposure to heat. Data pertaining to the decay or loss of heat acclimation is sparse and variable within the literature. However, it is generally agreed that the improvement in f_c, which develops earlier during an acclimation regimen, is lost more rapidly than are the thermoregulatory improvements (Lind and Bass, 1963; Williams *et al.*, 1967; Pandolf *et al.*, 1977). Williams *et al.* (1967) found ~50% of the f_c and ~25% T_c adaptation were lost within 6-7 days, with 100% and 50% (respectively) losses by 18-21 days. As a rule of thumb, the equivalent of *one day of acclimation is lost every two days* (Givoni and Goldman, 1973). However, Pandolf *et al.* (1977) found that subjects with a high V_{O2peak}, and pre-existing acclimation state, lost acclimation effects more slowly. It appears that factors such as the magnitude of the thermal strain, the duration of acclimation and the number of exposures influence the rate of decay.

To maintain heat acclimation, *it is recommended that one additional heat exposure be used for each five days away from significant heat sources or exposures.*

5. References.

Adams, J.M., Fox, R.H., Grimby, G., Kidd, D.J., and Wolff, H.S. (1960). Acclimatization to heat and its rate of decay in man. *J. Physiol.* 152:26P-27P.

Allan, J.R., Crowdy, J.P., and Haisman, M.F. (1965). The use of a vapour-barrier suit from the practical induction of artificial acclimatization to heat: I. Winter experiment. Army Personnel Research Establishment. Report 4. Ministry of Defence. U.K.

Allan, J.R., and Wilson, C.G. (1971). Influence of acclimatization on sweat sodium concentration. *J. Appl. Physiol.* 30:708-712.

Araki, T., Matsushita, K., Umeno, K., Tsujino, A., and Toda, Y. (1981). Effect of physical training on exercise-induced sweating in women. *J. Appl. Physiol.* 51:1526-1532.

Armstrong, L.E., Costill, D.L., Fink, W.J., Bassett, D., Hargreaves, M., Nishibata, I., and King, D.S. (1985). Effects of dietary sodium on body and muscle potassium content during heat acclimation. *Eur. J. Appl. Physiol.* 54:391-397.

Armstrong, L.E., Hubbard, R.W., DeLuca, J.P., and Christensen, E.L. (1986). Self-paced heat acclimation procedures. U.S. Army Research Institute of Environmental Medicine. Technical report number T8/86. Natick. U.S.A.

Armstrong, L.E., Hubbard, R.W., DeLuca, J.P., and Christensen, E.L. (1987). Heat acclimatization during summer running in the northern United States. *Med. Sci. Sports & Exerc.* 19:131-136.

Armstrong, L.E., and Maresh, C.M. (1991). The induction and decay of heat acclimatisation in trained athletes. *Sports Med.* 12:302-312.

Armstrong, L.E., and Pandolf, K.B. (1988). Physical training, cardiorespiratory physical fitness and exercise-heat tolerance. In: Pandolf, K.B., Sawka, M.N., and Gonzales, R.R. *Human performance physiology and environmental medicine at terrestrial extremes.* Benchmark Press. Indianapolis. Pp. 199-226.

Avellini, B.A., Kamon, E., and Krajewski, J.T. (1980). Physiological responses of physically fit men and women to acclimation to humid heat. *J. Appl. Physiol.* 49:254-261.

Avellini, B.A., Shapiro, Y., Fortney, S.M., Wenger, C.B., and Pandolf, K.B. (1982). Effects of heat tolerance on physical training in water and on land. *J. Appl. Physiol.* 53:1291-1298.

Barnett, A., and Maughan, R.J. (1993). Response of unacclimatized males to repeated weekly bouts of exercise in the heat. *Brit. J. Sports Med.* 27:39-44.

Bass, D.E. (1963). Thermoregulatory and circulatory adjustments during acclimatization to heat in man. In: Hardy, J.D. *Temperature: its measurement and control in science and industry.* Reinhold. New York. Pp. 299-305.

Bean, W.B., and Eichna, L.W. (1943). Performance in relation to environmental temperature. *Fed. Proc.* 2:144-158.

Cadarette, B.S., Sawka, M.N., Toner, M.M., and Pandolf, K.B. (1984). Aerobic fitness and the hypohydration response to exercise-heat stress. *Aviat. Space & Environ. Med.* 55:507-512.

Candas, V. (1987). Adaptation to extreme environments. Thermophysiological changes in man during humid heat acclimation. In: Dejours. *Comparative physiology of environmental adaptations.* Volume 2. Karger, Basel. Pp. 76-93.

Candas, V., Libert, J.P., and Vogt, J.J. (1980). Effect of hidromeiosis on sweat drippage during acclimation to humid heat. *Eur. J. Appl. Physiol.* 44:123-133.

Candas, V., Libert, J.P, and Vogt, J.J. (1983). Sweating and sweat decline of resting men in hot humid environments. *Eur. J. Appl. Physiol.* 50:223-232.

Chen, W.Y., and Elizondo, R.S. (1974). Peripheral modification of thermoregulatory function during heat acclimation. *J. Appl. Physiol.* 37:367-373.

Cohen, J.S., and Gisolfi, C.V. (1982). Effects of interval training on work-heat tolerance of young women. *Med. Sci. Sports Exerc.* 14:46-52.

Crowdy, J.P., and Haisman, M.F. (1965). The use of a vapour-barrier suit from the practical induction of artificial acclimatization to heat: II. Summer experiment. Army Personnel Research Establishment. Report 4. Ministry of Defence. U.K.

Davies, C.T.M. (1981). Effect of acclimatization to heat on the regulation of sweating during moderate and serve exercise. *J. Appl. Physiol.* 50:741-746.

Dawson, B. (1994). Exercise training in sweat clothing in cool conditions to improve heat tolerance. *Sports Med.* 17:233-244.

Dreosti, A. O. (1935). The results of some investigations into the medical aspects of deep mining on the Witwatersrand. *J. Chem. Metal. & Mining Soc. S.A.* Nov:102-129.

Duncan, M.T., and Horvath, S.M. (1988). Physiological adaptations to thermal stress in tropical asians. *Eur. J. Appl. Physiol.* 57:540-544.

Eichna, L.W., Bean, W.B., Ashe, W.F., and Nelson, N. (1945). Performance in relation to environmental temperature. Reactions of normal young men to hot, humid (simulated jungle) environment. *Bull. Johns Hopkin's Hosp.* 76:25-58.

Eichna, L.W., Park, C.R., Nelson, N., Horvath, S.M., and Palmes, E.D. (1950). Thermal regulation during acclimatization in hot dry (desert type) environment. *Am. J. Physiol.* 163:585-597.

Edholm, O.G., Fox, R.H., Adam, J.M., and Goldsmith, R. (1963). Comparison of artificial and natural acclimatization. *Fed. Proc.* 22:709-715.

Fox, R.H. (1968). A review of studies on the physiology of heat stress. Army Personnel Research Committee Report 68/A1. Ministry of Defence. U.K.

Fox, R.H., Goldsmith, R., Hampton, I.F.G., and Hunt, T.J. (1967). Heat acclimatization by controlled hyperthermia in hot-dry and hot-wt climates. *J. Appl. Physiol.* 22:39-46.

Fox, R.H., Goldsmith, R., Hampton, L.F.G., and Lewis, H.E. (1964). The nature of the increase in sweating capacity produced by heat acclimatisation. *J. Physiol.* 171:368-376.

Fox, R.H., Goldsmith, R., Kidd, D.J., and Lewis, H.E. (1963). Blood flow and other thermoregulatory changes with acclimation to heat. *J. Physiol.* 166:548-562.

Garden, J.W., Wilson, I.D., and Rasch, P.J. (1966). Acclimatization of healthy young adult males to a hot-wet environment. *J. Appl. Physiol.* 21:665-669.

Gisolfi, C.V. (1973). Work-heat tolerance derived from interval training. *J. Appl. Physiol.* 35:349-354

Gisolfi, C.V., and Cohen, J.S. (1979). Relationships among training, heat acclimation, and heat tolerance in men and women: the controversy revisited. *Med. Sci. Sports & Exerc.* 11:56-59.

Gisolfi, C.V., and Robinson, S. (1969). Relations between physical training, acclimatisation, and heat tolerance. *J. Appl. Physiol.* 26(5):530-534.

Greenleaf, J.E. (1964). Lack of artificial acclimatization to heat in physically fit subjects. Nature. 203:1072.

Greenleaf, J.E., and Greenleaf, C.J. (1970). Human acclimation and acclimatization to heat. A compendium of research. NASA Technical Memorandum. NASA TM X-62,008. Ames Research Center, Moffett Field. U.S.A.

Havenith, G., and van Middendorp, H. (1986). Determination of the individual state of acclimatization. *IZF report 1986-27.* TNO Institute for Perception. Soesterberg, Netherlands.

Hellon, R.F., Jones, R.M., Macpherson, R.K., and Weiner, J.S. (1956). Natural and artificial acclimatisation to hot environments. *J. Physiol.* 132:559-576.

Hellon, R.F., and Lind, A.R. (1955). Circulation in the hand and forearm with repeated daily exposures to humid heat. *J. Physiol.* 128:57P-58P.

Henane, R. (1980). Acclimatization to heat in man: giant or windmill, a critical appraisal. Twenty-eighth International Congress on Physiological Sciences. Pp. 275-284.

Henane, R., and Valatx, J.L. (1973). Thermoregulatory changes induced during heat acclimatization by controlled hyperthermia in man. *J. Physiol.* 230:255-271.

Henane, R., Flandrois, R, and Charbonnier, J.P. (1977). Increase in sweating sensitivity by endurance conditioning in man. *J. Appl. Physiol.* 43:822-828.

Hensel, H. (1981). Thermoreception and temperature regulation. In: *Monographs of the Physiological Society.* Number 38. Academic Press. London.

Hessemer, V., Zeh, A., and Bruck, K. (1986). Effects of passive heat adaptation and moderate sweatless conditioning on responses to cold and heat. *Eur. J. Appl. Physiol.* 55:281-289.

Horowitz, M., and Meiri, U. (1993). Central and peripheral contributions to control of heart rate during heat acclimation. *Pflugers Arch.* 422:386-392.

Houmard, J.A., Costill, D.L., Davis, J.A., Mitchell, J.B., Pascoe, D.D., and Robergs, R.A. (1990). The influence of exercise intensity on heat acclimation in trained subjects. *Med. Sci. Sports & Exerc.* 22(5):615-620.

Inoue, Y., Nakao, M., Okudaira, S., Ueda, H., and Araki, T. (1995). Seasonal variation in sweating responses of elder and younger men. *Eur. J. Appl. Physiol.* 70:6-12.

Jessen, C. (1990). Thermal afferents in the control of body temperature. In: Schonbaum, E., and Lomax, P. Thermoregulation. Physiology and biochemistry. Pergamon Press. New York. Pp. 153-184.

Kenney, L.W., and Johnson, J.M. (1992). Control of skin blood flow during exercise. *Med. Sci. Sports Exerc.* 24:303-312.

Kok, R. (1973). Heat tolerance of Bantu undergoing acclimatization. *So. Afr. Med. J.* 47:960.

Libert, J.P., Amoros, C., de Nisi, J., Muzet, A., Fukuda, H., and Ehrhart, J. (1988). Thermoregulatory adjustments during continuous heat exposure. *Eur. J. Appl. Physiol.* 57:499-506.

Libert, J.P., Candas, V., and Vogt, J.J. (1983). Modifications of sweating responses to thermal transients following heat acclimation. *Eur. J. Appl. Physiol.* 50:235-246.

Lind, A.R., and Bass, D.E. (1963). Optimal exposure time for development of acclimatization to heat. *Fed. Proc.* 22:704-708.

Marcus, P. (1972). Heat acclimatization by exercise-induced elevation of body temperature. *J. Appl. Physiol.* 33:283-288.

Miller, D.A. (1984). Heat acclimation procedures developed for use by the U.S. Marine Corps aboard ship en route to hot weather operations. Naval Medical Research Institute Report number NMRI-CO1-DAM:rh-3902. Bethesda, U.S.A.

Mitchell, D., Senay, L.C., Wyndham, C.H., van Rensberg, A.J., Rogers, G.G., and Strydom, N.B. (1976). Acclimatisation in a hot, humid environment: energy exchange, body temperature, and sweating. *J. Appl. Physiol.* 40:768-778.

Nadel, E.R. (1979). Control of sweating rate while exercising in the heat. *Med. Sci. Sports & Exerc.* 11:31-35.

Nadel, E.R., Pandolf, K.B., Roberts, M.F., and Stolwijk, J.A.J. (1974). Mechanisms of thermal acclimation to exercise and heat. *J. Appl. Physiol.* 37:515-520.

Nielsen, M. (1938). Die regulation der korpertemperatur bei muskelarbiet. *Skand. Arch. Physiol.* 79:193-230.

Nielsen, B., Hales, J.R.S., Strange, S., Juel Christensen, N., Warberg, J., and Saltin, B. (1993). Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *J. Physiol.* 460:467-485.

Ogawa, T., Ohnishi, N., Yamashita, Y., Sugenoya, J., Asayama, M., and Miyagawa, T. (1988). Effect of facial cooling during heat acclimation process on adaptive changes in sweating activity. *Jap. J. Physiol.* 38:479-490.

Ohnishi, N., Ogawa, T., Sugenoya, J., Asayama, M., and Yamashita, Y. (1986). Characteristics of the increase in sweating capacity induced by physical conditioning in cool environment. *J. Aichi Med. Univ. Assoc.* 14:663-669.

Pandolf, K.B. (1979). Effects of physical training and cardiorespiratory fitness on exercise-heat tolerance: recent observations. *Med. Sci. Sports & Exerc.* 11:60-65.

Pandolf, K.B., Burse, R.L., and Goldman, R.F. (1977). Role of physical fitness in heat acclimatisation, decay, and reinduction. *Ergonomics,* 20(4):399-408.

Pandolf, K.B., Cadarette, B.S., Sawka, M.N., Young, A.J., Francesconi, R.P, and Gonzalez, R.R. (1988). Thermoregulatory responses of middle-aged and young men during dry-heat acclimation. *J. Appl. Physiol.* 65:65-71.

Pitts, G.C., Johnson, R.E., and Consolazio, F.C. (1944). Work in the heat as affected by water, salt and glucose. *Am. J. Physiol.* 142:253-259.

Piwonka, R.W., and Robinson, S. (1967). Acclimatization of highly trained men to work in severe heat. *J. Appl. Physiol.* 22:9-12.

Piwonka, R.W., Robinson, S., Gay, V.L., and Manalis, R.S. (1965). Acclimatization of men to heat by training. *J. Appl. Physiol.* 20:379-384.

Regan, J.M., Macfarlane, D.J., and Taylor, N.A.S. (1996). An evaluation of the role of skin temperature during heat adaptation. *Acta. Physiol. Scand.* 158:365-375.

Roberts, M.F., and Wenger, C.B. (1979). Control of skin circulation during exercise and heat stress. *Med. Sci. Sports & Exerc.* 11:36-41.

Roberts, M.F., Wenger, C.B., Stolwijk, J.A.J., and Nadel, E.R. (1977). Skin blood flow and sweating changes following exercise training and heat acclimation. *J. Appl. Physiol.* 43: 133-137.

Robinson, S., Turrell, E.S., Belding, H.S., and Horvath, S.M. (1943). Rapid acclimatization to work in hot climates. *Am. J. Physiol.* 140:168-176.

Rowell, L.B. (1974). Human cardiovascular adjustments to exercise and thermal stress. *Physiol. Rev.* 54:75-139.

Rowell, L.B. (1983). Cardiovascular adjustments to thermal stress. In: *Handbook of Physiology - The cardiovascular system, Peripheral Circulation and Organ Blood Flow*, J.T. Shepard and F.M. Abboud (Eds). Bethesda, MD: American Physiological Society, 3(2):976-1023.

Saltin, B., and Hermansen, L. (1966). Esophageal, rectal and muscle temperature during exercise. *J. Appl. Physiol.* 21:1757-1762.

Sato, F., Owen, M., Matthes, R., Sato, K., and Gisolfi, C.V. (1990). Functional and morphological changes in the eccrine sweat gland with heat acclimation. *J. Appl. Physiol.* 69:232-236.

Sato, K., and Sato, F. (1983). Individual variations in structure and function of human eccrine sweat gland. *Am. J. Physiol.* 245:R203-R208.

Sciaraffa, D., Fox, S.C., Stockmann, and Greenleaf, J.E. (1980). Human acclimation and acclimatizzation to heat: a compendium of research - 1968-1978. NASA Technical Memorandum. NASA 81181. Ames Research Center, Moffett Field. U.S.A.

Senay, L.C. (1979). Effects of exercise in the heat on body fluid distribution. *Med. Sci. Sports & Exerc.* 11:42-48.

Senay, L.C., Mitchell, D., and Wyndham, C.H. (1976). Acclimatisation in a hot, humid environment: body fluid adjustments. *J. Appl. Physiol.* 40:786-796.

Shapiro, Y., Hubbard, R.W., Kimbrough, C.M., and Pandolf, K.B. (1981). Physiological and hematologic responses to summer and winter dry-heat acclimation. *J. Appl. Physiol.* 50:792-798.

Shvartz, E., Bhattacharya, A., Sperinde, S.J., Brock, P.J., Sciaraffa, D., and Van Beaumont, W. (1979). Sweating responses during heat acclimation and moderate conditioning. *J. Appl. Physiol.* 46:675-680.

Shvartz, E., Saar, E., Meyerstein, N., and Benor, D. (1973). A comparison of three methods of acclimatisation to dry heat. *J. Appl. Physiol.* 34:214-219.

Stolwijk, J.A.J., Roberts, M.F., Wenger, C.B., and Nadel, E.R. (1977). Changes in thermoregulation and cardiovascular function with heat acclimation. In: Nadel, E.R. *Problems with temperature regulation during exercise.* Academic Press. New York. Pp. 77-90.

Sugenoya, J., Ogawa, T., Asayama, M., Miyagawa, T., Yamashita, Y., and Ohnishi, N. (1986). Involvement of the central sudomotor mechanism in an increased sweating capacity following heat acclimation. *J. Aichi Med. Univ. Assoc.* 14:653-661.

Turk, J. (1974). A reliable test of heat acclimatization for the army. Army Personnel Research Establishment Report 7/74. Ministry of Defence. Farnborough. U.K.

Turk, J. (1982). Artificial acclimatization to heat for the army: techniques, logistics and staffing. Army Personnel Research Establishment Memorandum 82M513. Ministry of Defence. Farnborough. U.K.

Turk, J., and Worsley, D.E. (1974). A technique for rapid acclimatization to heat for the army. Army Personnel Research Establishment Report 12/74. Ministry of Defence. Farnborough. U.K.

Wells, C.L., Constable, S.H., and Haan, A.L. (1980). Training and acclimatisation: effects on responses to exercise in a desert environment. *Aviat. Space & Environ. Med.* 51:105-112.

Williams, C.G., Wyndham, C.H., and Morrison, J.F. (1967). Rate of loss of acclimatization in summer and winter. *J. Appl. Physiol.* 22:21-26.

Wood, J.E., and Bass, D.E. (1960). Responses of the veins and arterioles of the forearm to walking during acclimatisation to heat in man. *J. Clin. Invest.* 39:825-833.

Wyndham, C.H. (1973). The physiology of exercise under heat stress. *Ann. Rev. Physiol.* 35:193-220.

Wyndham, C.H., and Heyns, A.J. (1973). The probability of heat stroke developing at different levels of heat stress. *Arch. Sci. Physiol.* 27:A545-A562.

Wyndham, C.H., and Jacobs, G.E. (1957). Loss of acclimatization after six days of work in cool conditions on the surface of a mine. *J. Appl. Physiol.* 11:197-199.

Yamazaki, F., Fujii, N., Sone, R., and Ikegami, H. (1994). Mechanisms of potentiation in sweating induced by long-term physical training. *Eur. J. Appl. Physiol.* 69:228-232.

DISTRIBUTION LIST

Heat Acclimation Procedures: Preparation for Humid Heat Exposure

Nigel A.S. Taylor, Mark J. Patterson, Jodie M. Regan and Denys Amos

AUSTRALIA

1. DEFENCE ORGANISATION

Task Sponsor
DGOPHS

S&T Program
Chief Defence Scientist
FAS Science Policy
AS Science Corporate Management
shared copy
Director General Science Policy Development
Counsellor Defence Science, London (Doc Data Sheet)
Counsellor Defence Science, Washington (Doc Data Sheet)
Scientific Adviser to MRDC Thailand (Doc Data Sheet)
Director General Scientific Advisers and Trials/Scientific Adviser Policy and Command (shared copy)
Navy Scientific Adviser
Scientific Adviser - Army
Air Force Scientific Adviser
Director Trials

Aeronautical and Maritime Research Laboratory
Director
Chief, AOD
Dr S. Oldfield

Electronics and Surveillance Research Laboratory
Director
Chief, LOD
Dr J. Manton

Research Leader - Dr D.B. Paul
Task Manager Mr D. Amos
Author(s):
Dr N.A.S. Taylor
Mr M.J.Patterson
Ms J.M. Regan

DSTO Library
Library Fishermens Bend
Library Maribyrnong
Library Salisbury (2 copies)

Australian Archives
Library, MOD, Pyrmont (Doc Data sheet)

Capability Development Division
Director General Maritime Development
Director General Land Development (2 Copies)
Director General C3I Development (Doc Data Sheet only)

Navy
SO (Science), Director of Naval Warfare, Maritime Headquarters Annex, Garden Island, NSW 2000.

Army
ABCA Office, G-1-34, Russell Offices, Canberra (4 copies)
SO (Science), HQ 1 Division, Milpo, Enoggera, Qld 4057
NAPOC QWG Engineer NBCD c/- DENGRS-A, HQ Engineer Centre Liverpool Military Area, NSW 2174
SO (Science) 3BDE

Intelligence Program
DGSTA, Defence Intelligence Organisation

i. **Corporate Support Program (libraries)**
OIC TRS, Defence Regional Library, Canberra
Officer in Charge, Document Exchange Centre (DEC), 1 copy
*US Defence Technical Information Centre, 2 copies
*UK Defence Research Information Center, 2 copies
*Canada Defence Scientific Information Service, 1 copy
*NZ Defence Information Centre, 1 copy
National Library of Australia, 1 copy

2. **UNIVERSITIES AND COLLEGES**

Australian Defence Force Academy
Library
Head of Aerospace and Mechanical Engineering
Deakin University, Serials Section (M list), Deakin University Library
Senior Librarian, Hargrave Library, Monash University
Librarian, Flinders University
James Cook University - Dr R. Griffiths

3. **OTHER ORGANISATIONS**

NASA (Canberra)
AGPS
NT Institute of Sports - Dr D. Hatcher

OUTSIDE AUSTRALIA

4. **ABSTRACTING AND INFORMATION ORGANISATIONS**

INSPEC: Acquisitions Section Institution of Electrical Engineers
Library, Chemical Abstracts Reference Service
Engineering Societies Library, US
Materials Information, Cambridge Scientific Abstracts, US
Documents Librarian, The Center for Research Libraries, US

5. **INFORMATION EXCHANGE AGREEMENT PARTNERS**
Acquisitions Unit, Science Reference and Information Service, UK
Library - Exchange Desk, National Institute of Standards and Technology, US

SPARES (10 copies)

Total number of copies: 72

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION)
Heat acclimation procedures: preparation for humid heat exposure.	Document (U) Title (U) Abstract (U)
4. AUTHOR(S)	5. CORPORATE AUTHOR
Nigel A.S. Taylor, Mark J. Patterson, Jodie M. Regan and Denys Amos	Aeronautical and Maritime Research Laboratory PO Box 4331 Melbourne Vic 3001

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TR-0580	AR-010-356	Technical Report	October 1997

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
510/207/0826	ADF 95/065	DGOPHS	27	95

13. DOWNGRADING/DELIMITING INSTRUCTIONS	14. RELEASE AUTHORITY
	Director Aeronautical and Maritime Research Laboratory

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE CENTRE, DIS NETWORK OFFICE, DEPT OF DEFENCE, CAMPBELL PARK OFFICES, CANBERRA ACT 2600

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CASUAL ANNOUNCEMENT YES

18. DEFTEST DESCRIPTORS

Physiological effects; Stress (physiology); Adaption(physiology); Acclimatisation; Exposure (physiology); Endurance (physiology); Heat; Humidity; Climatic changes

19. ABSTRACT

Thermal homeostasis is rigorously challenged under extremely hot conditions, particularly during prolonged exercise, with even highly trained individuals failing to maintain thermal homeostasis. As a consequence, the incidence of heat illness increases, particularly during the first five days of heat exposure. However, humans have evolved so that heat dissipation and conservation mechanisms are able to adapt to a range of environmental conditions. These physiological changes can be brought about in response to acute natural climatic changes, artificial heat exposure and to endurance exercise training. This report summarises the physiological changes accompanying heat adaptation and critically reviews heat adaptation procedures. Finally, recommendations are made concerning the implementation of heat adaptation procedures for military personnel. These recommendations include: specification of the thermal environment; the level of thermal strain; the use of exercise; exposure duration; and the subsequent maintenance of heat adaptation.